MEASUREMENT OF THE BROAD LINE REGION SIZE IN TWO BRIGHT QUASARS

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ABSTRACT

We present 4 years of spectrophotometric monitoring data for two radio-quiet quasars, PG 0804+762 and PG 0953+414, with typical sampling intervals of several months. Both sources show continuum and emission line variations. The variations of the Hβ line follow those of the continuum with a time lag, as derived from a cross-correlation analysis, of 93±30 days for PG 0804+762 and 111±55 days for PG 0953+414. This is the first reliable measurement of such a lag in active galactic nuclei with luminosity $L > 10^{45}$ erg s^{-1}. The broad line region (BLR) size that is implied is almost an order of magnitude larger than that measured in several Seyfert 1 galaxies and is consistent with the hypothesis that the BLR size grows as $L^{0.5}$.

Subject headings: galaxies: active — quasars: emission lines — quasars: individual (PG 0804+762, PG 0953+414)

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1. Introduction

Reverberation mapping has became one of the major tools for studying the distribution and kinematics of the gas in the broad line region (BLR) of active galactic nuclei (AGN) (see, e.g., Peterson 1993, Gondhalekar, Horne, & Peterson 1994). About a dozen Seyfert 1 galaxies have been successfully monitored so far. The time lags between the emission line and the continuum light curves measured in these objects can be interpreted in terms of the delayed response of the spatially-extended BLR to the ionizing continuum source. The best studied Seyfert 1 galaxy, NGC 5548, was monitored from the ground for over 5 years, and from space for several long periods (Korista et al. 1995, and references therein). Several other Seyfert 1s, such as NGC 4151 and Mrk 279, were observed for periods of order a year or less. While these observations have not uniquely determined the geometries of the BLRs, they have established that Seyfert 1 BLRs have sizes of the order of a few light-days to light-weeks.

While much progress has been achieved in reverberation mapping of Seyfert galaxies, relatively little is known about the BLR size in high-luminosity AGN. Few spectrophotometric monitoring attempts of quasars have been made and most of these (e.g., Zheng et al 1987; Perez Penston & Moles 1989; Gondahalekar 1990; Korista 1991; Jackson et al. 1992) resulted in no clear lag determinations, either due to poor sampling, or because no line variability was detected. Some monitoring projects have yielded controversial results, such as, for example, the *International Ultraviolet Explorer* campaign on 3C 273. O'Brien & Harris (1991) report a lag of 74 days between the Lyα emission line and the continuum, while Ulrich et al. (1993) argue that the line variations are only marginally significant.

Since mid-1991, we have been monitoring a well-defined sub-sample of 28 quasars from the Palomar-Green (PG) sample (Schmidt & Green 1983) with typical sampling intervals of $1-4$ months. Results of the first 1.5 years were presented in Maoz et al. (1994; Paper I) where it was shown that most quasars had undergone continuum variations in the range of $10\% - 70\%$. Balmer line variations that are correlated with the continuum changes were detected in several objects. Based on those preliminary data, it was demonstrated that the emission-line response times in several quasars is $\lesssim 6$ months. Reverberation mapping of these objects therefore requires several years, with sampling intervals of less than a few months. The need for a long temporal baseline is illustrated by the previous results for PG 0953+414, for the periods 1987-89 and 1991-92, presented in Paper I. Despite continuum variations of $\sim$35%, no clear line variations were detected. As we will show in this *Letter*, with a monitoring campaign of longer duration we detect the line variability in this object.

We present 4 years of data for two radio-quiet quasars from our sample, PG 0804+762 and PG 0953+414 (Table 1). The two quasars show clear evidence of a time lag between the Balmer lines and the continuum variations. We use this to set significant constraints on the BLR size in these high-luminosity objects. In § 2 we describe the observations, present the light curves, and carry out a cross-correlation analysis to determine the BLR size. In § 3 we discuss the results.

2. Observations and Analysis

The observations and the reduction procedure are described in detail in Paper I. We repeat here the main points. The observations were carried out using the Steward Observatory 2.3m telescope and the Wise Observatory 1m telescope. For each quasar, the spectrograph slit was rotated to the appropriate position angle so that a nearby comparison star was observed along with the object. Wide slits ($4.5''$ at Steward, $10''$ at Wise) were used to minimize the effects of atmospheric dispersion at the non-parallactic position angle. The quasar flux is calibrated relative to that of the comparison star. This technique provides excellent calibration even during poor weather conditions, and accuracies of order $1\% - 2\%$ can easily be achieved.

Observations typically consisted of two consecutive exposures of the quasar/star pair. Total exposure times were usually 40 minutes long at Steward and 2 hours at Wise. The spectroscopic data were reduced using standard IRAF[5] routines. The consecutive quasar/star flux ratios were compared to test for systematic errors in the observations. The ratios almost always reproduced to 0.5-1.5% at all wavelengths and observations with ratios larger than 5% were discarded.

For both quasars we examined the best S/N spectra and chose line-free spectral bands suitable for setting the continuum underlying the emission lines and the wavelength limits for integrating the line fluxes. The spectral regions for Hβ and the continuum bands are given in Table 1. The line and continuum fluxes were measured automatically for all epochs by calculating the mean flux in the continuum bands and summing the flux above a straight line in f_λ connecting the continuum bands straddling the emission line.

Figure 1 shows the continuum measurements (on the blue side of Hβ) for PG 0804+762, together with B-band photometry from Paper I, and the Hβ light curve. Observations of this quasar used different comparison stars at Wise and at Steward (see Paper I). Note the excellent agreement between these completely independent measurements. The continuum variability (defined as $[F_{max}/F_{min} - 1]$) is 40% and the Hβ variability is $\sim$18%. The continuum variability time scale, defined as the width of the continuum auto-correlation function at 0.5 correlation, is 320 days. The Hβ light curve clearly follows the continuum. It is smoother than the continuum light curve and does not show the shorter and weaker spikes. Nearly identical behavior and variability are seen in the Hα light curve (not shown).

Figure 2 shows the corresponding light curves for PG 0953+414. During the 4-year period, the continuum varied by 35% while the Hβ light curve, which appears

[5] IRAF (Image Reduction and Analysis Facility) is distributed by the National Optical Astronomy Observatories, which are operated by AURA, Inc., under cooperative agreement with the National Science Foundation.

Table 1
OBSERVATIONAL PARAMETERS

	PG 0804+762	PG 0953+414
z	0.100	0.239
B magnitude	$\sim$15.2	$\sim$15.1
Luminosity[a]	$\sim 2\times10^{45}$	$\sim 5\times10^{45}$
blue continuum band[b]	5224–5264 Å	5238–5278 Å
red continuum band[b]	5598–5630 Å	6288–6320 Å
Hβ range[b]	5266–5474 Å	5906–6086 Å

[a]Between 0.1–1μm in units of erg s^{-1}, assuming a power-law continuum ($f_\nu \propto \nu^{-\gamma}$) normalized at the observed optical flux ($H_0 = 75$ km s^{-1}Mpc^{-1}, $q_0 = 0.5$, $\gamma = 0.5$).

[b]Wavelengths given in observer's frame.

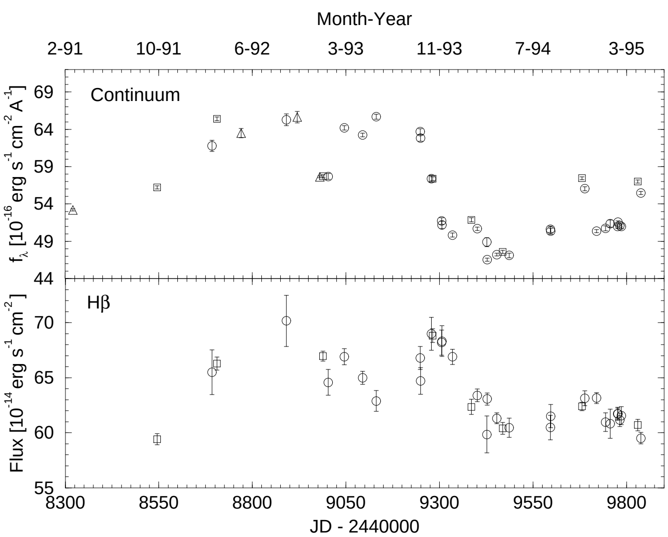

Fig. 1.— PG 0804+762 light curves. Top panel – continuum flux density at 5244 Å. Bottom panel – Hβ emission-line flux. Circles are spectrophotometric measurements from Wise Observatory and squares are from Steward Observatory. Triangles are B-band photometric measurements from Wise Observatory (see Paper I).

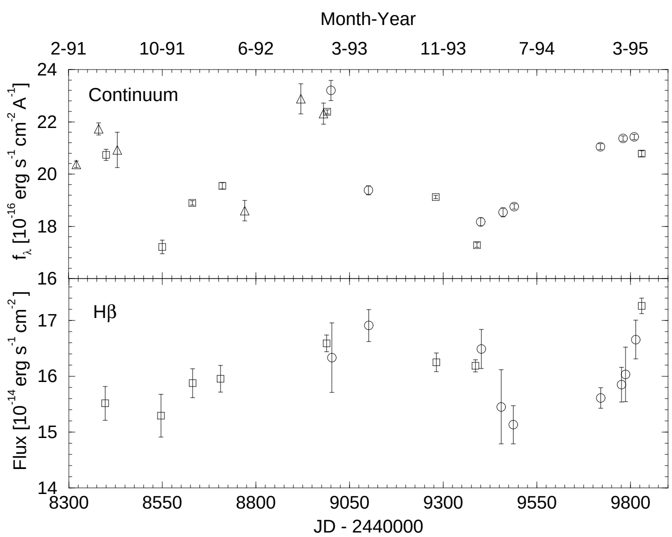

Fig. 2.— PG 0953+414 light curves. Top panel – continuum at 5268 Å. Bottom panel – Hβ. Symbols as in Fig. 1.

to follow the continuum, has a typical amplitude of 13%. The continuum variability time scale, defined as above, is 200 days. The Hγ line (not shown here) exhibits similar variations to Hβ.

We have used two methods for correlating the line and continuum light curves. The partly interpolated cross-correlation function (PICCF) of Gaskell & Peterson (1987) and Gaskell (1994) and the z-transform discrete correlation function (ZDCF) of Alexander (1996). The second method, which is an improvement of the discrete correlation function (DCF; Edelson & Krolik 1988), applies Fisher's z transformation to the correlation coefficients, and uses equal population bins rather than the equal time bins used in the DCF. The cross correlations of the Hβ and the continuum light curves for the two objects are shown in Figure 3. Both cross-correlation methods yield similar results. The ZDCF for PG 0953+414 has few points since its light curves contain fewer measurements and the number of bins scales as the square of the number of measurements. Nevertheless, its agreement with the PICCF is good and indicates that the interpolation done in the PICCF did not introduce an artificial correlation. In both quasars, the Hβ flux lags the contin-

Table 2
CROSS CORRELATION FUNCTION TIME LAGS (DAYS)

	PG 0804+762	PG 0953+414
PICCF[a] centroid	102	115
ZDCF[a] centroid	84	107
BLR size[b]	85±27	90±44

[a]See § 2 for definition.

[b]Deduced from averaging centroid results and applying a $(1+z)^{-1}$ factor.

uum by a few months and the cross-correlation function (CCF) peak is highly significant. We list in Table 2 the centroid of all points above 60% of the peak correlation. Since both correlation methods yield similar centroid results, we adopt the mean lag implied by the two methods as our measure of the BLR radius. We defer to a future paper discussion of various complications involved in associating an observed time-lag with a BLR size, e.g., the dependence of the peak of the CCF on the nature of the continuum variability, the possible non-linear response of the Balmer line intensity to the continuum flux variations, or the possibility that the ionizing continuum may behave differently from the observed continuum.

To estimate the uncertainty in the PICCF time lags, we have carried out Monte-Carlo simulations as described in Maoz & Netzer (1989). For each object the simulation involves a linear interpolation of the observed continuum light curve and the calculation of the expected line light-curve for a chosen BLR geometry. These continuum and line light curves are then repeatedly sampled at random in a seasonal pattern resembling the observing sequence, simulated measurement errors are added, and the PICCF and its centroid location are calculated for each simulated pair. We have tried a variety of spherical geometries and computed, for each, the cross-correlation centroid distribution. The distribution is approximately Gaussian. The width of the distribution is a measure of the uncertainty in the lag. The central width that contains 68% of all expected lags is an estimate of the 1σ error. This corresponds to ±30 days for PG 0804+762 and ±55 days for PG 0953+414. These uncertainties are adopted in the discussion below.

3. Discussion

Spectrophotometric monitoring of PG 0804+762 and PG 0953+414 have revealed a clear correlation and lag between the continuum and Balmer-line light curves. All Seyfert 1 galaxies that have been studied in this way have time-averaged luminosities of 4×10^{44} erg s^{-1} at most, while the PG quasars yield measures of the time lag in AGN with luminosities exceeding 10^{45} erg s^{-1}. We have found that the Hβ emission line lags the continuum by 93±30 days in PG 0804+762 and by 111±55 days in PG 0953+414. Since measured AGN time lags are an indicator of the characteristic BLR size, our results allow us to search for a correlation of the BLR size with source luminosity. When comparing lags, the same emission lines should be used in all objects since different emission lines can have different time lags in a given object (see, e.g., Peterson 1993). Balmer lines are useful since their lag has been measured in most AGN where reverberation mapping has been attempted.

Figure 4 compares the BLR size of 12 AGN, as deduced from cross-correlating the Balmer lines with the optical continuum light curves, to their 0.1–1 μm luminosity (defined in Table 1). We restrict ourselves to measurements where a significant correlation of the line and continuum light curves has been detected. The BLR radius, R_{BLR}, is the mean of values in the literature for the time lag of a given object, corrected by a $(1+z)^{-1}$ factor. Caution must be taken when interpreting the diagram, since each study has used its own method to deduce R_{BLR} and its uncertainty. The error bars on R_{BLR} are a combination of the quoted uncertainties in the various references, as well as the spread in values reported in the literature for a given object. The uncertainty in the luminosity, L, is set by the observed variability range. For the Seyfert nuclei ($\log L < 44.5$) alone there is no clear correlation given the narrow luminosity range sampled. Adding the results for PG 0804+762 and PG 0953+414 introduces a possible trend, and indicates that R_{BLR} may scale with L. Under the simple assumptions that the shape of the ionizing continuum in AGN is independent of L, and that all AGN are characterized by the same ionization parameter and BLR gas density (as indicated by the generally-similar observed line ratios), $R_{BLR} \propto L^{0.5}$ is expected. A line with this slope is shown in Figure 4. While this is not the result of a proper fit to the data, such a trend is consistent with our results. The relation between R_{BLR} and L (if one exists), yet to be determined from our complete quasar sample, may hold important clues to the nature of these objects. In particular, using line-profile information, an AGN mass-luminosity relation can eventually be derived.

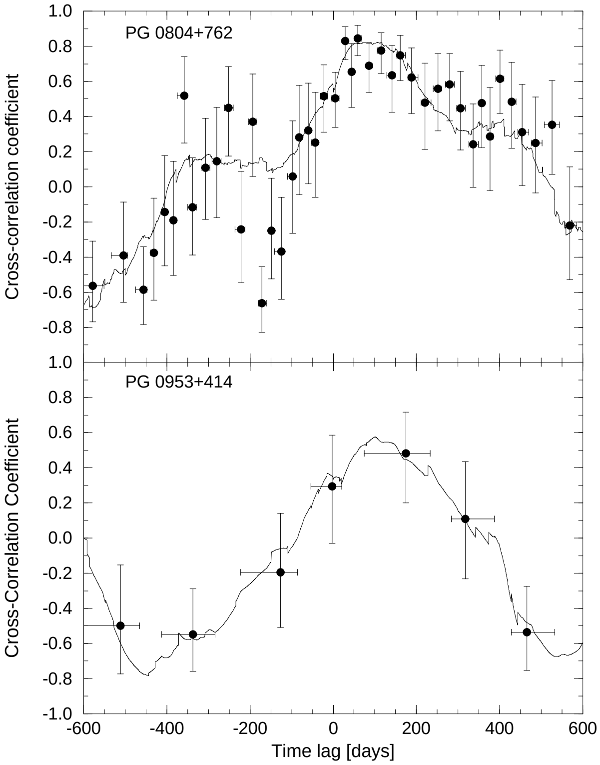

Fig. 3.— PICCF (solid line) and ZDCF (circles with error bars) of the Hβ light curve with the continuum light curve for PG 0804+762 (top) and for PG 0953+414 (bottom). Horizontal error bars indicate 1σ range of the ZDCF bin size (i.e., the standard deviation of time differences included in the bin).

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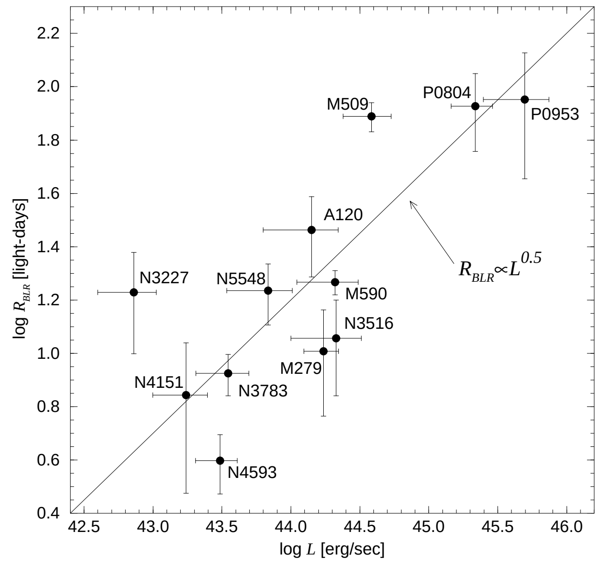

Fig. 4.— The BLR radius – luminosity relation. All sizes based on Balmer-line lags. References: NGC 5548 - Korista et al. (1995) and references therein; NGC 4151 - Maoz et al. (1991) and Kaspi et al. (1996); NGC 3227 – Salamanca, et al. (1994); NGC 3783 – Stirpe et al. (1994a); Akn 120 – Peterson (1988) and Peterson & Gaskell (1991); Mrk 279 – Maoz et al. (1990) and Stirpe et al. (1994b); NGC 3516 – Wanders et al. (1993); Mrk 590 – Peterson et al. (1993); NGC4593 – Dietrich et al. (1994); Mrk 509 – Carone et al. (1996); PG 0804+762 and PG 0953+414 – this work.

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